Army Research Laboratory

Development of a Nowcasting Method for Three-Dimensional Meteorological Data: Preliminary Report

by Teizi Henmi

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14. ABSTRACT

A nowcasting method for three-dimensional meteorological fields has been developed. Nowcasting is a method of diagnosing the current weather situation, and in this study is defined as an objective analysis of meterological parameters that have been currently observed. The Penn State University/National Center for Atmospheric Research (CAR) Mesoscale Model Version 5 (MM5) was utilized to obtain background data to combine with surface and upper-air observation data.

In this method, surface observations and the MM5 surface forecast/V data are composed using the successive correction method, followed by a similar composition of the upper-air sounding data and the MM5 forecast data using the same scheme. After these two steps, the similarity theory formulae, MARIAH, is used to combine surface data fields with upper-air data fields.

The method was applied to meteorological fields over the complex terrain centered at Salt Lake City, Utah.

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Summary

A nowcasting method for three-dimensional meteorological fields has been developed. Nowcasting is a method of diagnosing the current weather situation and, in this study, is defined as an objective analysis of meteorological parameters that have been currently observed. The Pennsylvania State University/National Center for Atmospheric Research (NCAR) Mesoscale Model Version 5 (MM5) was utilized to obtain background data to combine with surface and upper-air observation data.

In this method, the surface and upper-air fields are initially analyzed both independently and univariately. The surface observations and the MM5 surface forecast data are composed using the successive correction method, followed by a similar composition of the upper-air sounding data and the MM5 forecast data (on σ-levels) using the same scheme. After these two steps, the similarity theory formulae, MARIAH, are used to combine surface data fields with upper-air data fields, by calculating the meteorological parameters at the σ-level next to the ground using the MARIAH formulae.

The nowcast method discussed was applied to meteorological fields over the complex terrain centered at Salt Lake City, Utah. It should be noted that the method described in this report is preliminary and needs further development.

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1. Introduction

Mesoscale forecasting models, such as the U.S. Army's Battlescale Forecast Model (BFM) and the Pennsylvania State University/National Center for Atmospheric Research (NCAR) Mesoscale Model Version 5 (MM5), generally produce reliable forecast fields of meteorological parameters. However, they also sometimes produce fields that are far from reality (Henmi, 2002 and 2003). For Army operations, accurate information obtained by using currently observed meteorological parameters is more desirable than simply relying on those fields obtained by a previously executed forecasting model. Nowcasting is a method of diagnosing the current weather situation, and in this study is defined as an objective analysis of meterological parameters that have been currently observed. If the current weather situation is accurately diagnosed, it may be possible to accurately forecast near-future weather situations.

In previous studies, the successive correction method (Sashegyi and Madala, 1994) has been successfully applied to nowcasting surface meteorological parameters over Oklahoma (Sauter et al., 2001) and Utah (Henmi, 2002). In the Oklahoma study, the BFM forecasting calculations were made over a model domain of 600 by 600 km, with a 61 by 61 grid mesh and 10 km grid increments. The BFM forecast data of temperature, dew point temperature, and wind vector components were composed with the observed data from selected sites in the Oklahoma Mesonet by the successive correction method. The results of the study showed that combining surface observation data with the BFM forecast fields could produce more accurate fields of the surface meteorological parameters than could either the model forecast or an objective analysis of observed data alone. In the Utah study, done over the model domain of 125 by 125 km, with 2.5 km grid increment, the following was concluded:

1. Temperature and dew point temperature can be accurately nowcasted by using the successive correction method. The BFM forecast data provided good background gridded data for these parameters. The combination of the observed data and the good background data resulted in surface temperature and dew point temperature fields that accurately represented the current fields.
2. Surface horizontal wind vector fields were greatly improved by the nowcasting method over the BFM forecast fields. The BFM forecasting calculation alone could not produce reliable surface wind vector fields, but by combining the forecast with observation, further improved wind fields could be obtained.

The objectives of this study are to develop a nowcasting method for three-dimensional meteorological data fields, by combining surface and upper-air sounding data with forecast fields produced by a locally run implementation of the MM5 and to examine the method by applying to the model domain over Utah. This report describes preliminary results of development and evaluation of the method. For Army operations in the battlefield, knowledge of accurate metrological condition is very important. The aim of this study is to provide that knowledge.

2. Nowcasting Method

2.1 MM5

The model used in this study is the distributed-memory version of the MM5, and its source code was obtained from the MM5 website (2001). The MM5 is based on non-hydrostatic dynamics and features a multinest capability along with many different physical parameterization options. The vertical levels in MM5 are defined by a non-dimensional quantity σ:

$$\sigma = \frac{p - p_t}{p_s - p_t} \tag{1}$$

where

p is the pressure, p_t is a specified constant top pressure, and p_s is the surface pressure. The value of σ is zero at the top and one at the surface.

For the present study, the following physics options are employed:

1. Planetary Boundary Layer (PBL) parameterization: Scheme used in the National Center for Environmental Prediction (NCEP) Medium Range Forecast Model (MRF) by Hong and Pan (1996).
2. Precipitation parameterization: A simple treatment of cloud microphysics based on Dudhia (1989) in which both ice and liquid phases are permitted for cloud and precipitation, but mixed phases are not permitted.
3. Cumulus parameterization: Grell's (1994) scheme that is based on the rate of destabilization or quasi-equilibrium, a simple single-cloud scheme with both updraft and downdraft fluxes and compensating motion determining the heating and moistening profile.
4. Radiation parameterization: Dudhia's scheme in which long wave and short wave radiation interact with the clear atmosphere, clouds, precipitation, and the ground (1989).
5. Ground temperature scheme: Multilayer soil temperature model.

2.2 Successive Correction Method

The MM5 forecasting data, containing hourly output data, is used as the background data for nowcasting temperature, dew point temperature, and horizontal wind vector components, u and v. The successive correction method that follows is used in this study:

If φ_a is the nowcasted value at the grid point (i, j), and φ_b (i, j) is the value of the background at the grid point, we can write

$$\varphi_a(i,j) = \varphi_b(i,j) + \sum_{k=1}^{m} w_{k,ij}(\varphi_{o,k} - \varphi_{b,k}) \tag{2}$$

where

$\varphi_{o,k}$ is the observation at the k^{th} location, $w_{k,ij}$ is the weight for each observation,

$\varphi_{b,k}$ is the value of the background at the observation point derived by a bilinear interpolation method, and m is the number of observations.

The weighting factor is defined as

$$w_{k,ij} = \frac{1}{r_{k,ij}^2} \tag{3}$$

where

$r_{k,ij}$ is the distance between the k^{th} observation point to grid point (i, j).

The method is repeated in an iterative fashion, so that the background field is updated by the latest analysis after each iteration:

$$\varphi_a(n+1) = \varphi_a(n) + \sum_{k=1}^{m} w_{k,ij}(\varphi_{o,k} - \varphi_{a,k}(n)) \tag{4}$$

where

$\varphi_a(n)$ is the value of the analysis at the grid point after the n^{th} iteration, and $\varphi_{a,k}$ is its value interpolated for the k^{th} location after the n^{th} iteration.

In this study, the iteration was repeated three times, for practical purposes, to obtain the final values.

Upper-air sounding data and MM5 forecast data are combined at σ levels as follows;

1. The σ-level of sounding data at pressure level p_n, $\sigma(p_n)$ is calculated by eq (1).
2. If σ(k) is between $\sigma(p_n)$ and $\sigma(p_{n+1})$, an arbitrary parameter φ of sounding data at σ(k) is interpolated as

$$\varphi(k) = \varphi(p_n) + \frac{(\varphi(p_{n+1}) - \varphi(p_n))}{(\sigma(p_{n+1}) - \sigma(p_n))}(\sigma(k) - \sigma(p_n)) \tag{5}$$

3. A new three-dimensional field of an arbitrary parameter φ is generated by combining φ(k) with the MM5 forecast data at σ(k) level by the successive correction method.

Standard MM5 forecast data contains (via similarity theory extrapolation) temperature and water vapor mixing ratio at 2 magl, and wind vector components at 10 magl. New surface data fields

are created by combining these MM5 surface data fields with surface observation data by application of the successive correction method.

2.3 Similarity Formulae, MARIAH

The equations and approach for determining the similarity scaling constants for wind, temperature, and specific humidity, referred to as MARIAH (Rachele et al., 1995), are used to combine the surface and three-dimensional analyses. For practical purposes, it is assumed that the lowest layer above ground of the three-dimensional analysis is modified by new surface data. Details of MARIAH can be seen in the reference. Here, the approach is briefly described.

1. Potential temperature θ, specific humidity q, wind speed V, and wind direction are calculated from the MM5 three-dimensional fields.

2. The scaling height z^* is calculated as

$$z^* = \frac{z_2 - z_1}{\ln(z_2 / z_1)} = \frac{\Delta z}{\Delta \ln z} \tag{6}$$

and

$$\begin{aligned} \Delta V &= V(z_2) - V(z_1) \\ \Delta \theta &= \theta(z_2) - \theta(z_1) \\ \Delta q &= q(z_2) - q(z_1) \end{aligned} \tag{7}$$

Here z_1 is the height of the surface observation, and z_2 is the height of the lowest layer above ground of the MM5 vertical σ- coordinate. For θ and q, z_1 is 2 magl, and for V, z_1 is 10 magl.

3. Depending on the stability of the atmosphere near the surface, the profiles of temperature, specific humidity, and wind speed are determined as

a. Unstable case ($\Delta\theta / \Delta z < 0$)

Monin-Obukhov scaling length L is calculated as

$$L = \frac{\theta_v (\Delta V)^2}{[\Delta\theta + 0.61\theta\Delta q] g \Delta \ln z} \tag{8}$$

$$\phi_m = (1 - 15\frac{z}{L})^{-1/4} \tag{9}$$

$$\phi_H = (1 - 15\frac{z}{L})^{-1/2} \tag{10}$$

$$V_* = \frac{k \Delta V}{\phi_m \ln(z_2 / z_1)} \tag{11}$$

$$\theta_* = \frac{k\Delta\theta}{\phi_H \ln(z_2 / z_1)} \tag{12}$$

$$q_* = \frac{k\Delta q}{\phi_H \ln(z_2 / z_1)} \tag{13}$$

Here k is the von Karman constant (0.4).

Wind speed, potential temperature, and specific humidity at the height z_2 are given as:

$$V(z_2) = V(z_1) + \frac{V^* \phi_m}{kz^*} \Delta z \tag{14}$$

$$\theta(z_2) = \theta(z_1) + \frac{\theta^* \phi_H}{kz^*} \Delta z \tag{15}$$

$$q(z_2) = q(z_1) + \frac{q^* \phi_H}{kz^*} \Delta z \tag{16}$$

b. <u>Stable case ($\Delta\theta / \Delta z > 0$)</u>

$$L = \frac{\theta(z_2)(1 + 0.61q(z_2))(\Delta V)^2}{[\Delta\theta + 0.61\theta\Delta q]g\Delta z} - 5z_2 \tag{17}$$

and

$$\phi_m = \phi_H = 1 + 5(z_2 / L) \tag{18}$$

$$V(z_2) = V(z_1) + \frac{V_*}{k}[\ln(\frac{z_2}{z_1}) + 5\frac{z_2 - z_1}{L}] \tag{19}$$

$$\theta(z_2) = \theta(z_1) + \frac{\theta_*}{k}[\ln(\frac{z_2}{z_1}) + 5\frac{z_2 - z_1}{L}] \tag{20}$$

$$q(z_2) = q(z_1) + \frac{q_*}{k}[\ln(\frac{z_2}{z_1}) + 5\frac{z_2 - z_1}{L}] \tag{21}$$

c. <u>Neutral case ($\Delta\theta / \Delta z = 0$)</u>

$$V(z_2) = V(z_1) + \frac{V_*}{k}\ln(\frac{z_2}{z_1}) \tag{22}$$

$$\theta(z_2) = \theta(z_1) + \frac{\theta_*}{k}\ln(\frac{z_2}{z_1}) \tag{23}$$

$$q(z_2) = q(z_1) + \frac{q_*}{k}\ln\frac{z_2}{z_1} \tag{24}$$

3. Application to the Utah Model Domain

3.1 MM5 Model Domain

The nowcast methodology discussed in the previous sections was applied to a model domain centered on Utah (fig. 1).

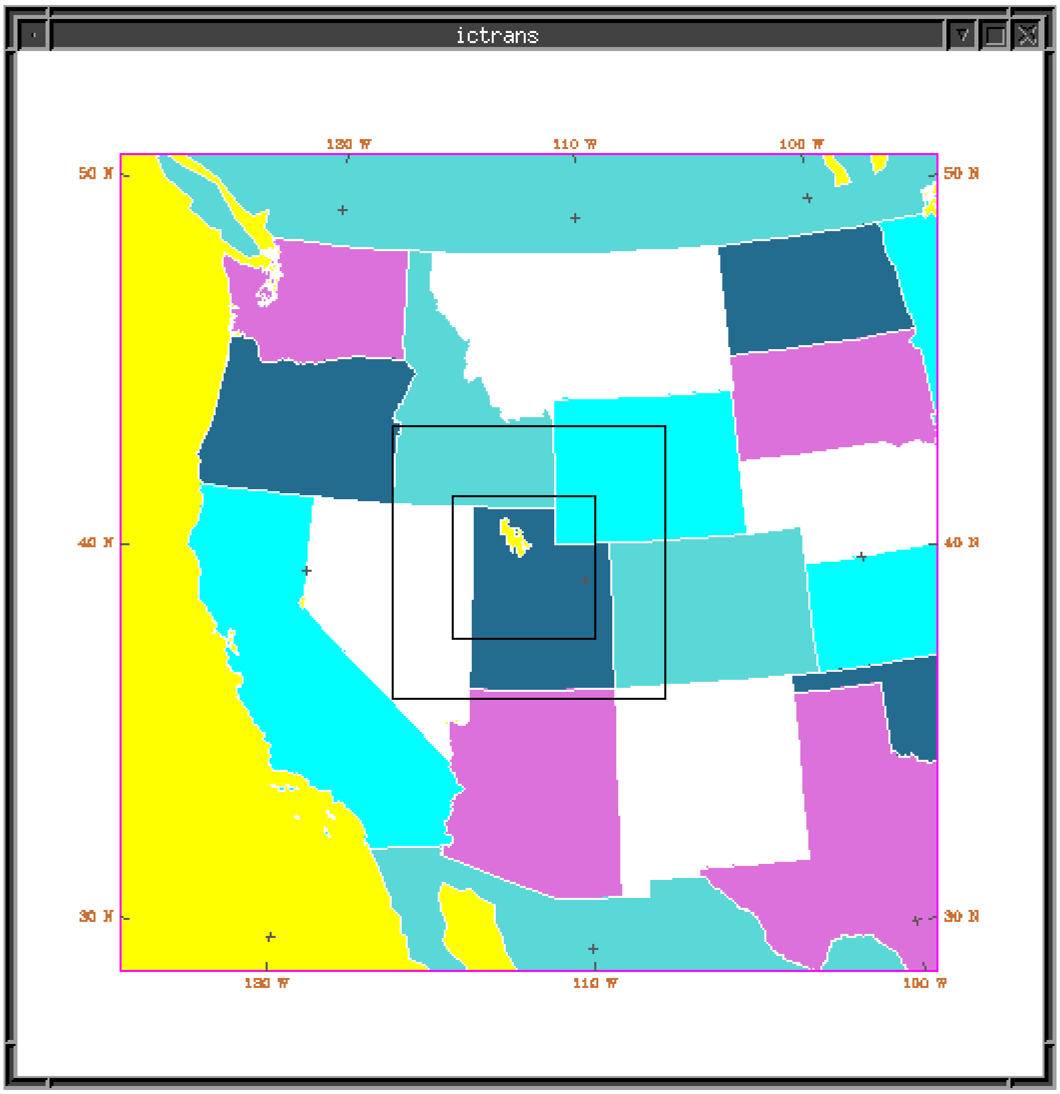

Figure 1. Geographical extents of the three MM5 computational domains.

The MM5 model domains 1 and 2 both have a horizontal mesh size of 55 by 55 grid points, while the innermost model domain 3 has a horizontal mesh size of 85 by 85. The grid increments (horizontal resolutions) of each domain are 45, 15, and 5 km, respectively. For the present study, the forecast fields for domain 2 are used as background data for the nowcasting algorithm, because there are four upper-air sounding stations located within the domain, (fig. 2). Figure 2 shows the MM5 terrain height contours for domain 2.

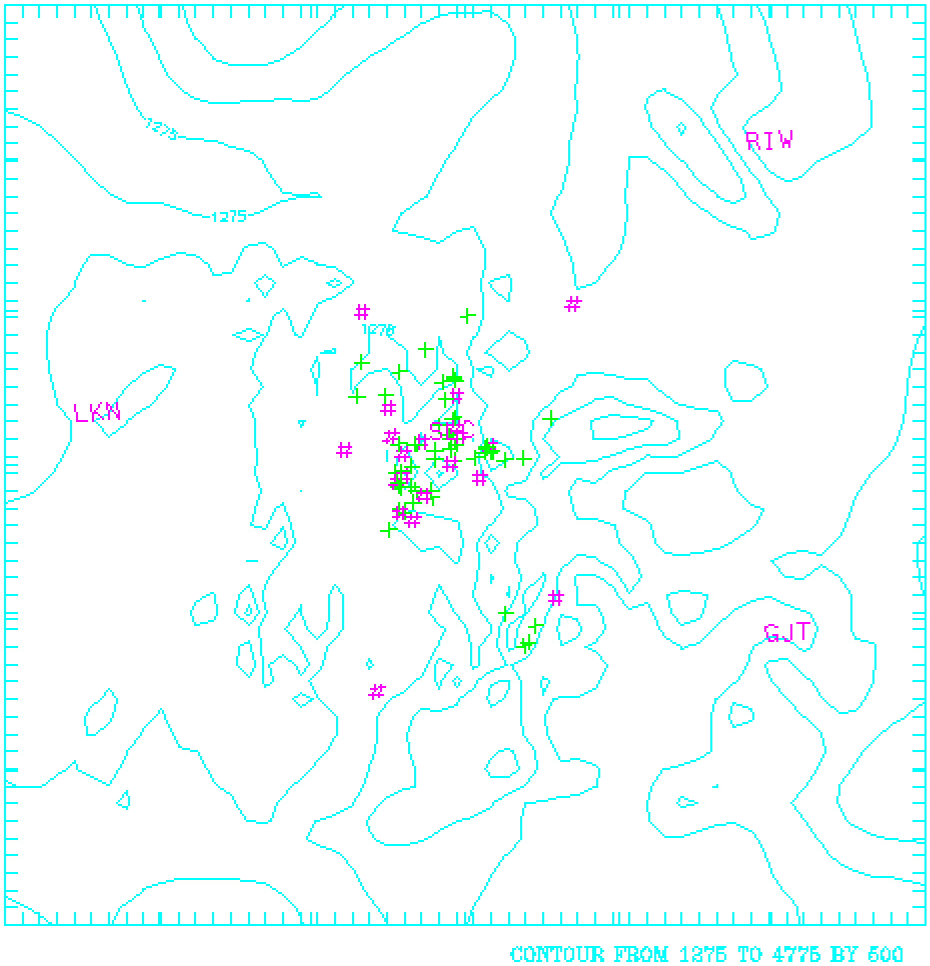

Figure 2. Terrain contours for MM5 model domain 2.

NOTES:
1. The locations of upper-air sounding stations are
 a. LKN (Elko, Nevada)
 b. SLC (Salt Lake City, Utah)
 c. RIW (Riverton Wyoming)
 d. GJT (Grand Junction, Colorado)
2. The symbol "#" represents the location of surface data used for producing nowcasting analyses.
3. The symbol "+" represents surface data used for statistical comparison of the nowcasting analyses.

In figure 2, the locations of upper-air sounding stations are represented as LKN, SLC, RIW, and GJT. In this study, the sounding data taken at LKN was used to produce the nowcasting analysis, while the data taken at SLC, RIW, and GJT were used to statistically compare the various nowcasted data. The symbol "#" represents the locations of surface observation sites whose data were used for producing the nowcasting analyses, and the symbol "+" represents observation sites whose data were compared to the nowcasting analyses to produce the statistics.

3.2 Meteorological Data

Figure 2 shows numerous surface observational data sites available for the MM5 model domain 2. The data are publicly available from the University of Utah Mesowest cooperative anonymous file transfer protocol (FTP) site[a]. Mesowest data, which is archived daily at ARL into an ASCII file called total.dat, includes observations taken over the past 24-h period, in 15 min intervals, for the western United States. A detailed description of Mesowest data can be found in Horel et al. (2002). Upper-air sounding data discussed previously were taken at 00:00 and 12:00 UTC and obtained from the University of Wyoming Atmospheric Sciences Department Web site[b].

Several times daily, the NCEP Aviation Model (AVN) data provides global gridded forecast information at 1° resolution. This data was used for initialization and time-dependent lateral boundary conditions for the MM5 model runs. (The AVN forecast data initialized at 18:00 UTC was used for this study and was obtained through the anonymous FTP site at NCEP.

These data sets, mentioned in the previous paragraph, were collected for a 15-day period in May 2003 during which nowcasts were both generated and statistically analyzed. For each nowcasting period, the MM5 was initialized at 18:00 UTC and run for 30 h (for background data), using the first 6 hours as a mesoscale spin-up period. Upper-air sounding data are available only at 00:00 and 12:00 UTC; therefore, nowcast calculations were made three times a day: at 00:00, 12:00, and 00:00 UTC (of the next day).

3.3 Statistical Parameters

The following statistical parameters were calculated for evaluating the quality of the nowcast analyses:

- Mean difference (MD)
- Mean absolute difference (AD)
- Root mean square error (RMSE)
- Root mean square vector error (RMSVE)
- Correlation coefficient (CC)
- Mean wind direction difference (MWDDF)

Details of these parameters are described in Henmi (2003).

For this report, these statistical parameters were calculated for the entire study period, inclusive of all 15 days and all analysis periods (3) per day.

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[a]Mesowest: http://www.met.utah.edu/ksassen/fars.html

[b]Upper-air data: http://www.met.utah.edu/ksassen/fars.html

4. Results

4.1 Nowcast (Forecast) Results of Surface Meteorological Parameters

Statistical parameters are calculated between the nowcast (forecast) data and surface observation data obtained at the sites marked as "+" in figure 2. Tables 1 and 2 show the values of statistical parameters, respectively, between the nowcast/observations and the MM5 forecast/observation.

Table 1. Statistical parameters between nowcast data and observed data.

	MD	AD	RMSE	CC
Temperature(˚C)	-.57	2.82	3.79	0.88
Dew point temperature (˚C)	-.57	2.62	4.01	0.71
Wind speed (m/s)	-.06	1.66	2.23	0.38
Wind vector x-component, u (m/s)	-.07	1.89	2.50	0.40
Wind vector y-component, v (m/s)	.24	2.10	2.91	0.44

NOTES:
1. RMSVE = 3.9 m/sec
2. MWDDF = 54.4˚
3. The number of data points used for the statistical calculations is approximately 1,300.

Table 2. Statistical parameters between forecast data and observed data.

	MD	AD	RMSE	CC
Temperature (˚C)	.25	3.25	4.19	.84
Dew point temperature (˚C)	2.17	3.56	4.72	.66
Wind speed (m/sec)	.55	2.00	2.56	.29
Wind vector x-component, u (m/sec)	.69	2.30	2.97	.31
Wind vector y-component, v (m/sec)	.73	2.49	3.36	.33

NOTES:
1. RMSVE = 4.5 m/sec
2. MWDDF = 57.4˚

The number of data points used for the statistical calculations is approximately 1300.

The statistical results shown in tables 1 and 2 were obtained by combining the data over all three daily analysis periods (00:00, 12:00, and 24:00 UTC). Figures 3 and 4 are scatter diagrams for temperature, between nowcast and observation and between forecast and observation respectively. Similarly, figures 5 and 6 are the scatter diagrams for dew point temperature, and figures 7 and 8 the scatter diagrams for wind speed.

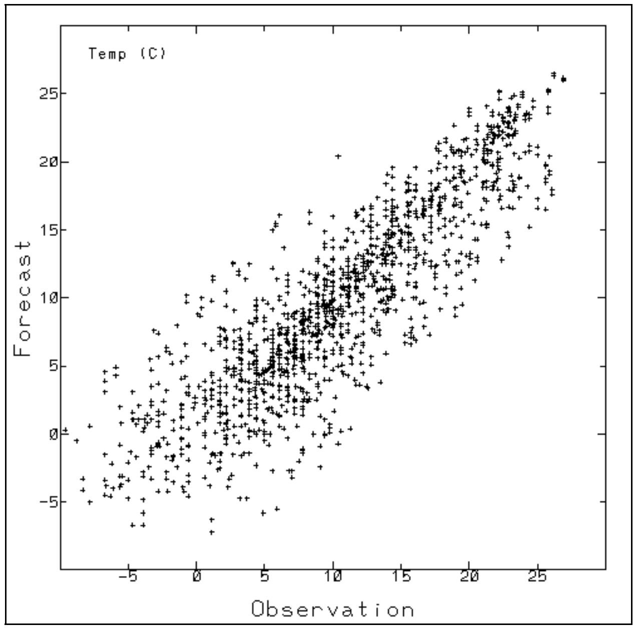

Figure 3. Scatter diagram between <u>nowcast</u> and observation data for temperature.

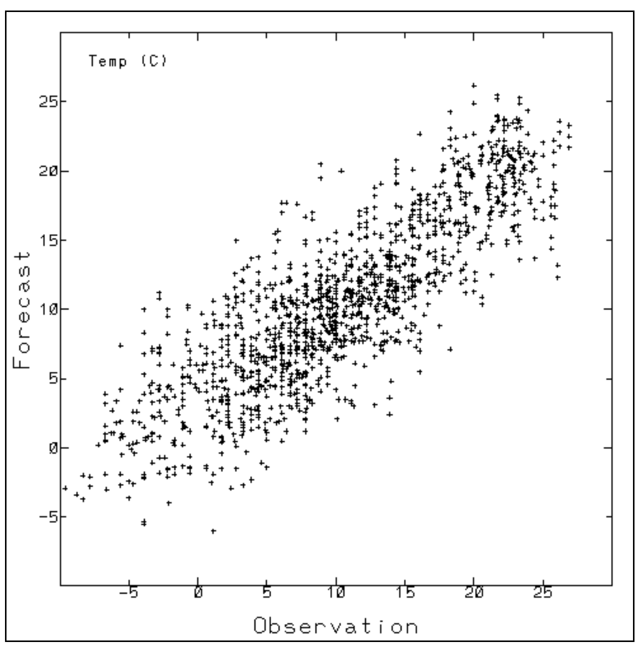

Figure 4. Scatter diagram between <u>forecast</u> and observation data for temperature.

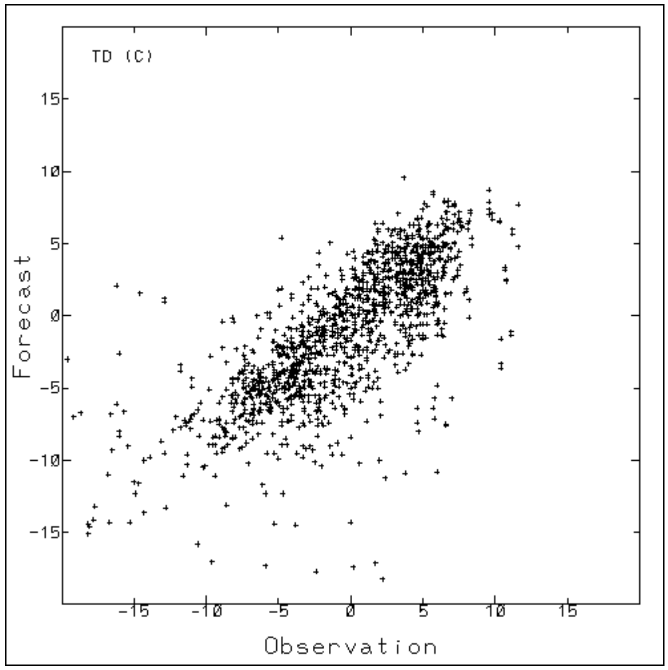

Figure 5. Scatter diagram between nowcast and observation for dew point temperature.

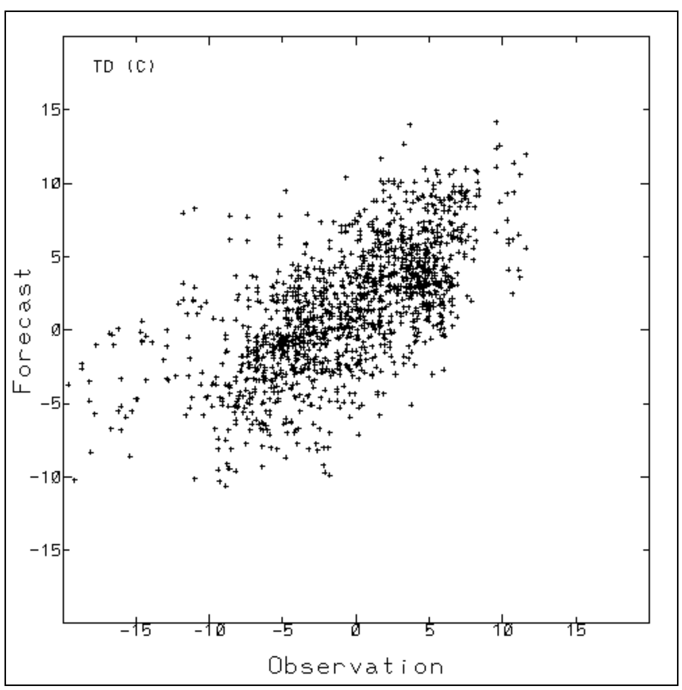

Figure 6. Scatter diagram between forecast and observation for dew point temperature.

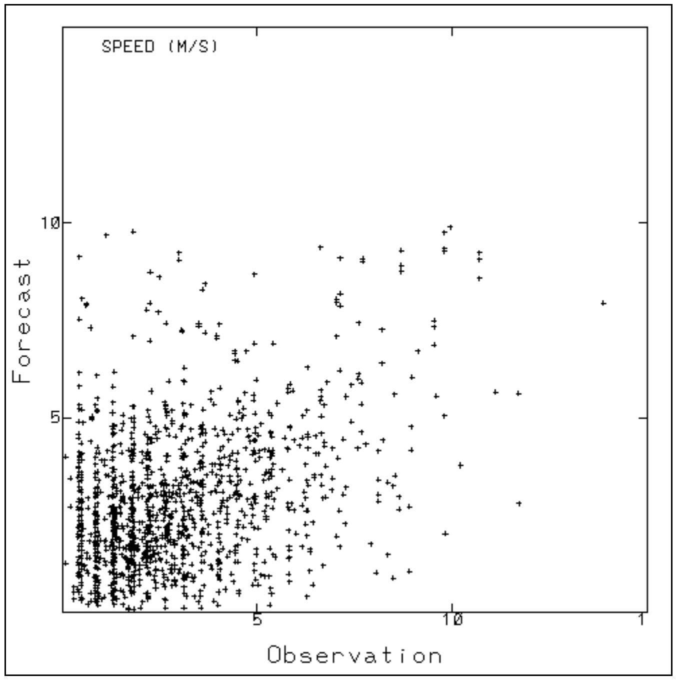

Figure 7. Scatter diagram between <u>nowcast</u> and observation for wind speed.

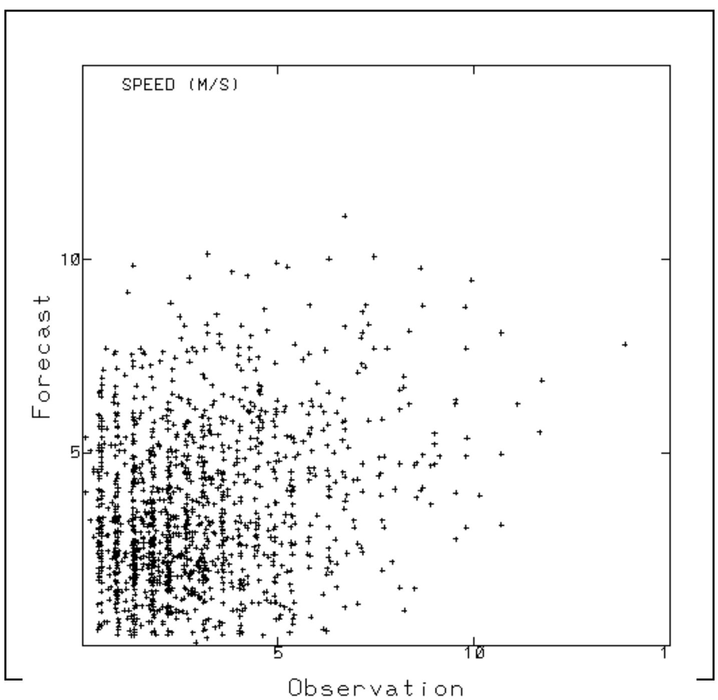

Figure 8. Scatter diagram between <u>forecast</u> and observation for wind speed.

Comparison of tables 1 and 2 and figures 3 to 8 show that surface meteorological fields can be improved by applying the nowcast analysis method, beyond what an earlier run numerical weather prediction (NWP) model forecast can produce. However, over complex terrains such as

the model domain used for this study, the nowcast analysis method shows limited capability (without further modifications and improvements) for improving surface meteorological fields. Better statistics may have been obtained for this study if the nowcast data had been generated on the MM5 5 km grid mesh. In a similar study over the state of Oklahoma, where the terrain features are not as complex as the model domain used for this study (Sauter et al. 2001), nowcasting calculations produced far improved surface meteorological fields over coincident NWP model forecast calculations.

4.2 Nowcast (Forecast) Results of Upper-Air Meterorological Parameters

As has been stated, upper-air sounding data obtained at LKN were used for generating the actual nowcast analyses, while data obtained at three other stations (SLC, RIV, GJT) were used as an independent sample for statistical comparison of the nowcast (forecast) data.

The results shown below are mean absolute differences between the nowcast analyses and the observational data, inclusive of all 15 days (May 2003) and all analysis periods (3) per day. In the following figures, green lines represent mean absolute differences between nowcast analyses and observations, and purple lines represent mean absolute differences between MM5 forecast calculations and observations. Mean absolute differences for temperature, dew point temperature, wind speed, and wind direction are shown.

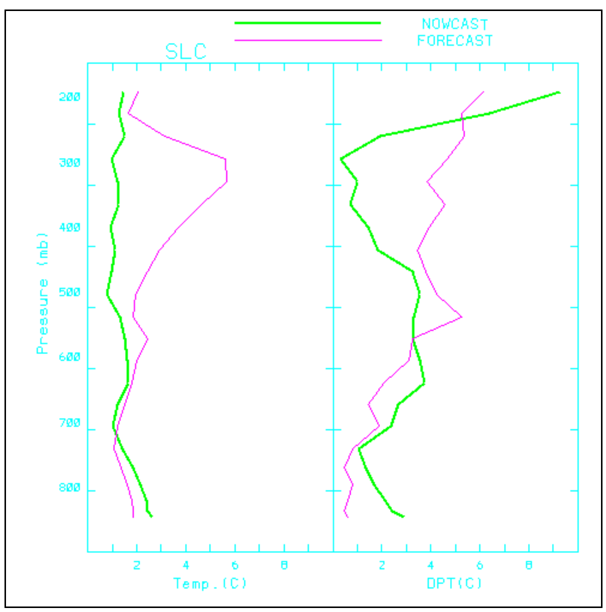

Figure 9. AD of nowcast (forecast) and observation data for temperature and dew point temperature for station SLC.

NOTES:

1. Green lines for nowcast
2. Purple lines for forecast

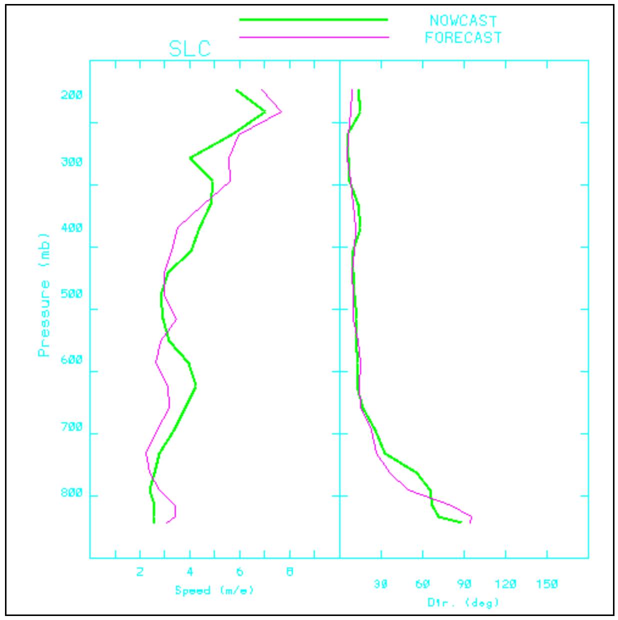

Figure 10. AD of nowcast (forecast) and observation for wind speed and direction for station SLC.

NOTES:
1. Green lines for nowcast
2. Purple lines for forecast

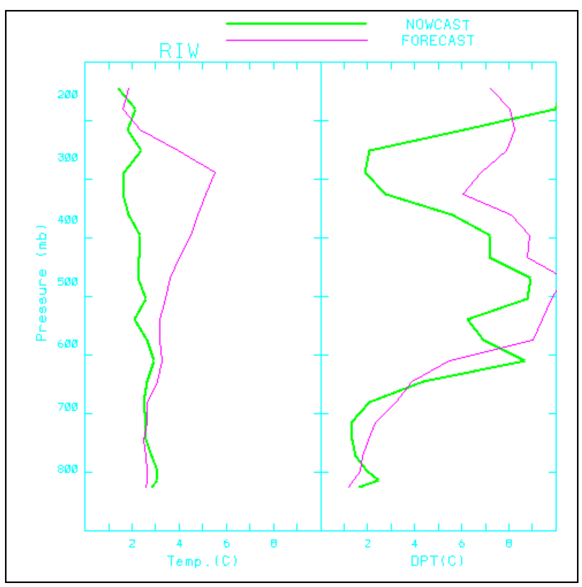

Figure 11. AD of nowcast (forecast) and observation data for temperature and dew point temperature for station RIV.

NOTES:
1. Green lines for nowcast
2. Purple lines for forecast

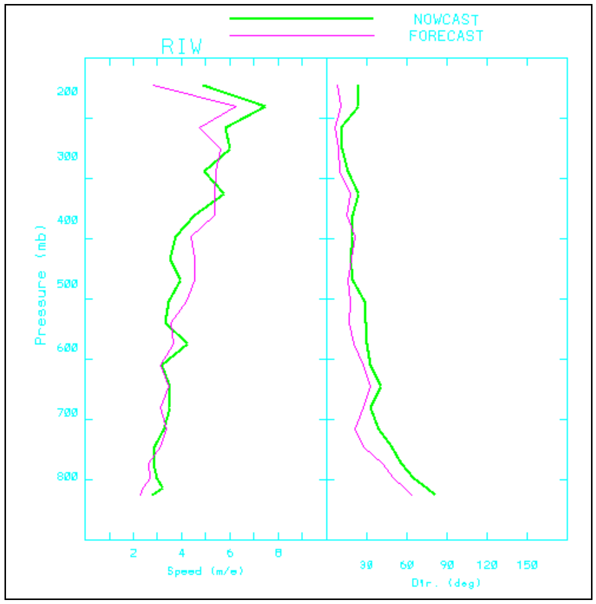

Figure 12. AD of nowcast (forecast) and observation for wind speed and direction for station RIV.

NOTES:
1. Green lines for nowcast
2. Purple lines for forecast

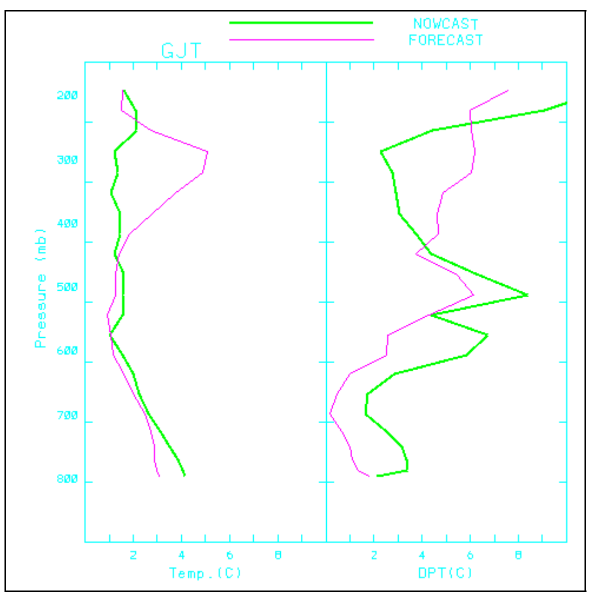

Figure 13. AD of nowcast (forecast) and observation data for temperature and dew point temperature for station GJT.

NOTES:
1. Green lines for nowcast
2. Purple lines for forecast

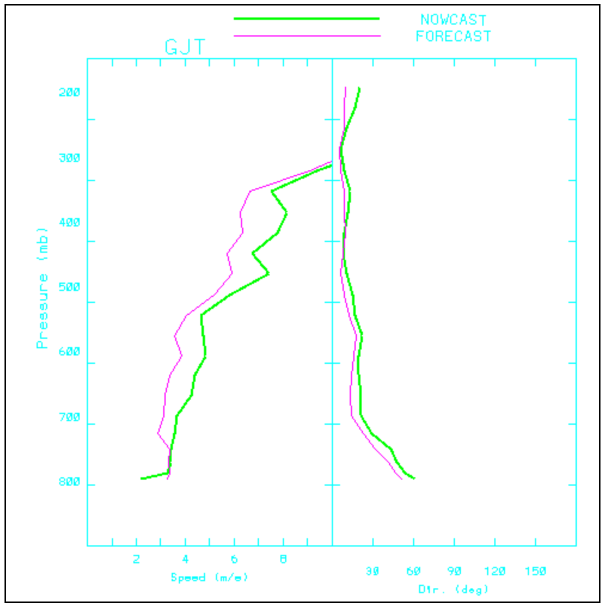

Figure 14. AD of nowcast (forecast) and observation data for wind speed and direction for station GJT.

NOTES:
1. Green lines for nowcast
2. Purple lines for forecast

By using just the data obtained at only one upper-air station (LKN) within the nowcast analysis domain of 810 by 810 km, the nowcast calculations still produced improvement in temperature and dew point temperature over coincident forecast calculations (see figures 9, 11, and 13). However, for wind speed and direction, the nowcast calculations did not produce significant improvements (figs. 10, 12, and 14).

5. Summary

A nowcasting method for rapidly updating three-dimensional meteorological fields has been developed. The method developed utilized MM5 forecasts as background first guess fields, used to combine surface and upper-air observation data in the nowcast analysis.

The method was applied for a 15-day period (in May 2003) over the complex terrain centered in Utah, and covering a domain of 810 by 810 km with a 15 km grid resolution. Twenty surface and one upper-air station data set within the analysis domain were used to produce the actual nowcast analyses, while about another forty surface and three upper-air station data were used as an independent data set for statistical comparisons. The following results were obtained:

1. Nowcast values of the surface meteorological parameters including temperature, dew point temperature, wind speed and direction agreed better statistically to observed data than did the coincident background MM5 forecast.
2. For upper-air meteorological parameters, nowcast values agreed better statistically to both temperature and dew point temperature observations than did coincident background MM5 forecasts. However, for wind speed and direction, no significant improvements were obtained by using the nowcast analysis over the coincident background MM5 forecast.

Further improvement of the present method is possible and necessary. For example, the upper-air sounding data can be combined with the background MM5 forecast data more easily on pressure-levels surfaces than on MM5 σ-level surfaces. Also, in the current application of the nowcast algorithm, the model domain uses an area of size 840 by 840 km and adopts a 15 km horizontal grid resolution. This was done in order for the current study to have four upper-air sounding data sets available for statistical evaluation. In previous studies (Mass et al. 2002, Henmi 2003), it was shown that the MM5 using a 5 km horizontal grid resolution can produce better forecast fields of surface meteorological parameters than similar runs using a 15 km horizontal grid resolution. Therefore, for operational use of the present method, it is desirable that the MM5 model domain be limited to a smaller overall area and be run at a horizontal grid resolution finer than 15 km. Besides offering better mesoscale detail, the higher resolution background fields will reduce terrain elevation mismatches between the model/analysis and the observation site.

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Acronyms

AD	Mean Absolute Difference
AVN	aviation model
BFM	Battlescale Forecast Model
CC	Correlation Coefficient
FTP	File Transfer Protocol
GJT	Grand Junction,Colorado
LKN	Elko, Nevada
MD	Mean Difference
MM5	Penn-State/National Center for Atmospheric Research (NCAR) Mososcale Model Version 5
MRF	Medium Range Forecast Model
MWDDF	Mean Wind Direction Difference
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NWP	Numerical Weather Prediction
PBL	Planetary Boundary Layer
RIW	Riverton, Wyoming
RMSE	Root Mean Square Error
RMSVE	Root Mean Square Vector Error
SLC	Salt Lake City, Utah

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